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# Laser welding head tailored to tube-sheet joint requirements for heat exchangers manufacturing

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Tube to tube-sheet joints in heat exchangers are currently welded by the orbital TIG process characterized by very high quality of the weld beads and good repeatability. However, due to high number of welds, a reduction in the welding cycle time would have an interesting impact on manufacturing costs and delays and laser welding technology is aimed to improve this factor.

The main disadvantage is the positioning accuracy required by the laser welding process since beam deviations from real joint cause lack of penetration. It is expected that the Orbital laser welding head developed under the European project ORBITAL will avoid this drawback.

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## 1. Introduction

Shell and tube heat exchangers are currently used in a wide range of industrial sectors such as power generation, chemical, petrochemical, or shipping sectors. European shell and tube heat exchangers market is undergoing a phase of cutthroat competition, which is adversely affecting the margin of domestic companies. Low cost heat exchanger suppliers from outside Europe have been fuelling the aggressive price war. Foreign entrants include suppliers from South Korea, China, and India as well. Surging metal prices and energy costs are also having a direct impact on profitability of heat exchanger manufacturers in Europe. Although companies are devising strategies to sustain their markets, pricing pressure is expected to continue in future.

Productivity improvements in the heat exchangers manufacturing are set to revitalize the shell and tube exchangers market. Indeed, the welding process plays a significant role in order to reduce the production cycle time, and thus reducing the delivery time, especially in shell and tube heat exchangers, where thousand of tube to tube-sheet welded joints are required. The orbital arc welding process for welding tube to tube-sheet joints was one of the major improvements introduced in this industrial sector in 1980s. This process is well established in different industrial sectors due to the high quality of the welded seams and the good repeatability of the process. The orbital arc welding process is an alternative to manual arc welding process because it increases the welding speed and ensures the repeatability of the welded seams [1]. Even so, the cycle time of the welding process is still very high, typically around forty seconds.

Laser welding technology is quite unknown in heat exchangers manufacturing sector. There are few applications for laser welding in this industrial sector. One of them is the application developed by Omega Engineering B.V for welding plates to make hydroformed heat exchangers [2]. Regarding to shell and tube heat exchangers, W.J.Han et al, 2001 and J.D. Kim et al., 2001 developed some laser processes to repair tubes of a heat exchanger of nuclear steam generators by the sleeving technique [3, 4]. For this type of application a pulsed Nd: YAG laser was used and different laser welding heads for the laser sleeving have been developed and patented [5, 6]. However the introduction of laser welding for tube to sheet joints in the manufacturing of heat exchangers and steam generators can introduce some improvements in the manufacturing process such as the increase of the welding speed, as demonstrated by R. Arias et al, 2010, and therefore a reduction of production time [7]. Furthermore due to the large number of welds to be done, the time between each operation is a critical point. The automation of the process, involving the use of the laser welding technology, would permit to reduce the time between welding operations. On the other hand, one of the main characteristics of laser welding is the high focused energy, allowing to get high power density in a spot size of 0,2-0,6mm. It results in a narrow fusion zone and low heat input so a reduction of rework operations can be expected decreasing the costs of rework, maintenance and repair of welded parts. As a result, the production cycle time would be reduced, improving productivity.

One of the main drawbacks induced by the high focused energy of lasers is the positioning accuracy required by the laser welding process. In order to propose a robust solution regarding positioning accuracy of the laser seam for tube to sheet joints, an orbital laser welding head has been developed under the European project ORBITAL. The ORBITAL Project (titled Design, development and evaluation of an orbital laser welding head) started in January 2011 due to the interest of implementing the laser welding process in industrial applications where orbital welding is needed.

The ORBITAL system consists in a new laser welding head adapted to the specific requirements of the orbital welding process and tailored for tube-to-sheet joints used in the production of heat exchangers. The system was developed in order to enhance the characteristics of the laser welding process: high-speed welding, real-time control, easy automation, data exchange, accuracy.

Due to the important size of heat exchangers, production takes place in large warehouses where vibrations generated by production processes or pieces manipulation are very common. This ORBITAL system will avoid vibration problems that could affect the laser welding process.

In this paper, the ORBITAL prototype system and the first results of the validation trials are presented.

## 2. Experimental

Mechanical elements of the ORBITAL laser welding head were built under the drawings and specifications developed in the project, see Fig. 1. The mechanical concept developed is as following:

- -Coupling system: an interface between the robot or CNC and the orbital part. The elements used for this function are on the shelf.
- Beam shaping: The first part of the processing head is composed by the lenses needed for the collimation and focusing of the beam. This part of the head is built using standard modules from the PRECITEC range YW30. Custom designed alignment modules are also used in this part of the head.
- Rotating part: it permits to generate the circular movement. This part of the head was designed in the project. Most elements are custom made for the purpose of the application.
- Positioning system: to ensure precision positioning of the head regarding the tube to be welded.
- Cover system: mainly for safety purpose, including different windows, in order to access to some internal parts of the head and sensors to be sure that these windows are closed during operation.



Fig. 1. Orbital laser welding head prototype

The control system of the ORBITAL laser welding head is based on a reconfigurable FPGA-based hardware (Field Programmable Gate Array) in order to be robust and real-time processing. The final user interface developed allows the end user to change the main welding parameters such as laser power, welding speed and rotation angle in order to control the start/stop welding operation. It is also possible to ramp the rotation speed and the laser power. Finally, it is also possible to load the pipe distribution into the control system so the user interface can show to the operator the welding state of each pipes (welded, not welded, or problem during welding). Figure 2 presents the user interface for the setting of parameters, and Figure 3 presents the user interface for the visualization of the operation state during the welding of the workpiece.

The first laboratory trials using the prototype system have already been performed. Optical elements have been aligned and electronic devices were set up in order to ensure that the laser beam performs the circular path. These set of trials performed with a 1kW IPG single mode fiber laser permitted to check the functionality of the ORBITAL system.

Once completed the laboratory trials, welding trials were performed in order to evaluate the system capacity. The system has been integrated in order to work in automatic mode and perform welding trials on different type of joints. The safety sensors, checking that the system is positioned onto the workpiece, were connected and the mechanical couplings between the robot and the head permitting x-z linear movement and angular tilting were installed, Figure 4. An ABB IRB 6600 robot has been used in order to hold the head. For the welding purpose, a 2kW fiber laser FL020 from ROFIN with a core diameter of 50 $\mu$ m has been used. Welding trials have been performed onto the two joint configurations presented in table 1.

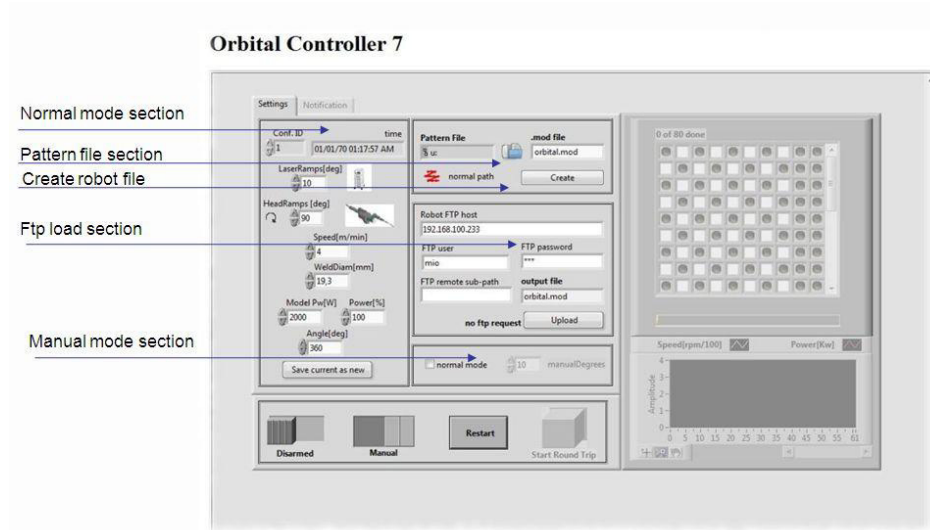


Fig. 2. User interface enabling the input of welding parameters and loading the tube distribution of the workpiece

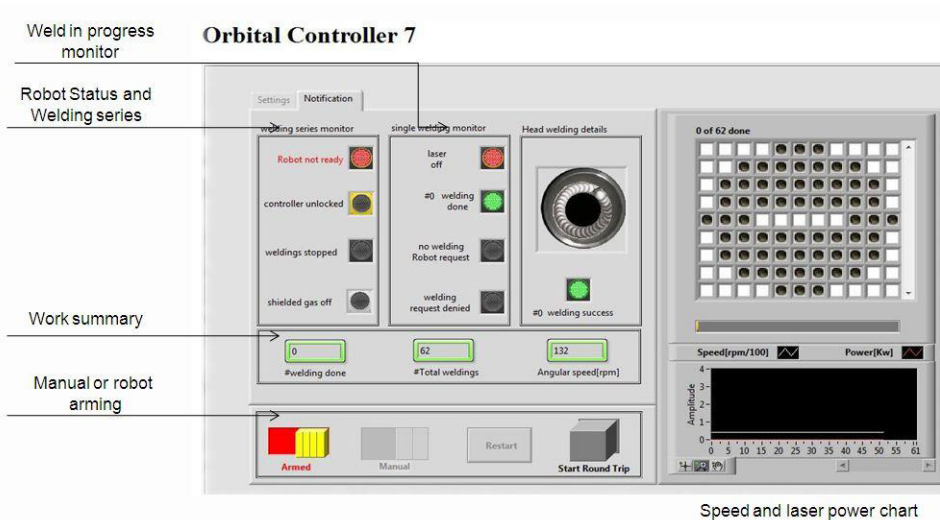


Fig. 3. User interface presenting the status of the ORBITAL system

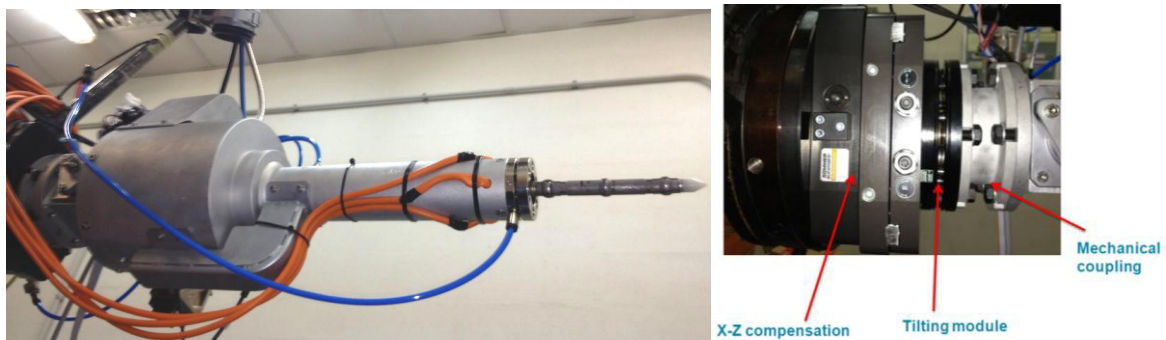


Fig. 4. (a) ORBITAL prototype welding head integrated onto a robot; (b) mechanical coupling modules between the robot and the ORBITAL head

Table 1. Joint configurations tested

Joint reference	Tube material	Sheet material	External diameter of the tube (mm)	Tube thickness (mm)
Joint 1	Nickel alloy 690	Nickel alloy 52	19,05	1
Joint 2	Stainless steel AISI304	Stainless steel AISI 316L	19,05	1

Two possible configurations resulting from the welding parameters are possible for this type of joint: complete or partial fusion of the tube thickness, Figure 5. In both cases, the laser is applied perpendicularly to the work piece surface. The difference of the final shape of the seam relies on the welding parameters. In any case, the reduction of the tube section should be avoided or reduced otherwise it may cause negative influence in flow circulation and cavitation within the pipes.

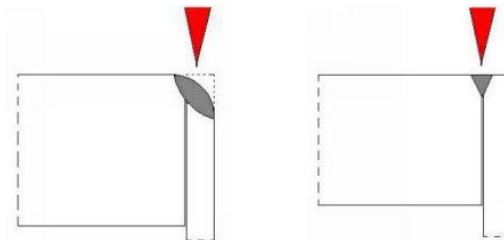


Fig. 5. (a) complete fusion of tube thickness; (b) partial fusion of tube thickness

The studied laser welding parameters were: laser power, welding speed, and shielding gas. As there are no examination requirements for laser welded tube to tube-sheet joints, requirements for TIG welds were used. Regarding to metallographic examination, weld beads must fulfil specific penetration and internal porosity requirements. Weld seams were subjected to several examination tests, to evaluate their quality. The following tests were performed: macrograph examinations and dye penetrant inspection.

### 3. Results and discussion

The laboratory trials permitted to validate the concept design of the prototype. After the fine alignment of the prototype, the basic performances of the system were demonstrated: circular welds with high precision centred with the tube to be welded. The laser power measurement confirmed low power losses into the head. The speed ramping and the laser power ramping were also successfully tested. Finally the maximum welding speed of 5m/min was validated. The trials performance is depicted in Figure 6. Figure 6 a) shows an image of the laser welding process on the specimen test, and Figure 6 b) shows some laser welded joints.

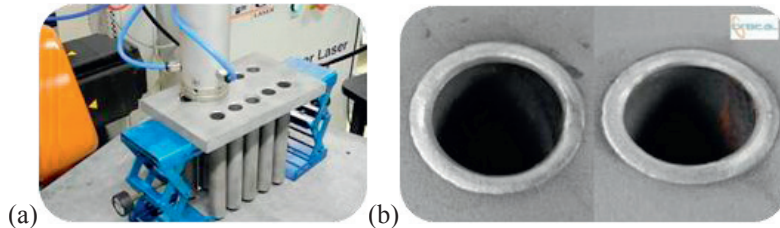


Fig. 6. (a) Laboratory set up; (b) Tube to tube-sheet joints laser welded

The welding trials performed following the laboratory trials permitted to validate the prototype functionality. It was possible to obtain seams with complete fusion or partial fusion of the tube thickness maintaining laser power at 2kW and adjusting welding speed. Figure 7 presents two cross sections obtained on tube to tube sheet joints of nickel alloy (joint 1). Figure 7 a) was welded using 2kW of laser power at a welding speed of 2m/min. The penetration depth reached 1,3mm. Figure 7 b) was welded using the same laser power, but at a lower speed: 1,5m/min. In this case, the penetration reached 1,6mm. In both cases Helium was used as shielding gas, with a flow rate of 30L/min.

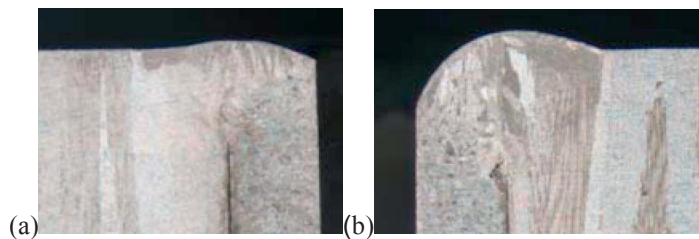


Fig. 7. (a) Cross section of joint 1 welded at 2m/min; (b) Cross section of joint 1 welded at 1,5m/min

Even so, the joining of tube to tube sheet is a complex process and requires very good tuning. A fundamental aspect to take into consideration is the good centering of the welding path, Figure 8 a). Deviations of tenths of millimeter are enough to reduce the leak path in a drastic way. One of the big improvements of the ORBITAL system when welding tube to sheet joints compared to standard commercial laser heads is the repetitiveness of the process. Once performed the tuning of centering of the beam path with the tube, the positioning of the beam onto the tubes is always the same thanks to the auto centering design. Figure 8 b) presents an example of misalignment due to bad tuning of the centering of the system with the joint. This is a cross section made on joint 2 welded with 2kW laser power and a welding speed of 1m/min. Helium was used also as shielding gas.



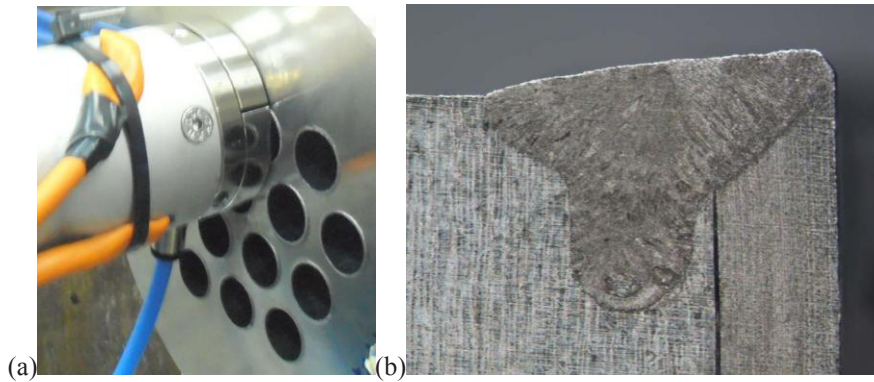


Fig. 8. (a) Positioning of the head onto a joint; (b) Cross section of joint 2 with deviation of the beam path

The visual aspect of the seam is also a critical point. Figure 9 a) shows a picture of a seam of joint 1 configuration presenting no visual defects and good penetration. The visual aspect of the joint is not as smooth as when using TIG orbital welding, Figure 9 b), however no indication was revealed from the dye penetrant testing. On the opposite, in the case of Figure 9 c), an external pore is visible by visual inspection, as well as using dye penetrant testing.

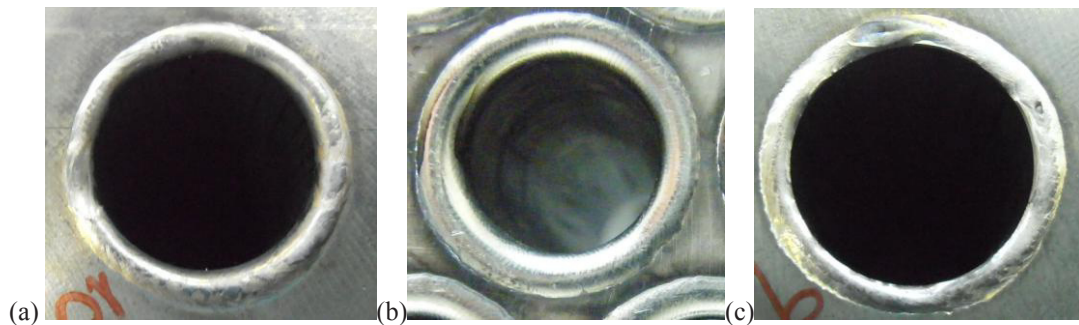


Fig. 9. (a) Joint 1 with no visual defects; (b) Joint 1 welded with TIG welding; (c) Joint 1 with a visual defect on the right part

Finally, it is also important to adjust the welding parameters in order to limit at the maximum the reduction of tube section. With laser welding it is possible to avoid section reduction of the pipes. When it occurs, it is normally less pronounced than in TIG welding. Figure 10 presents two cross sections of joint 2 configuration. Figure 10 a) was laser welded whereas Figure 10 b) was welded using TIG orbital welding. In both cases some reduction of the tube section is observed.

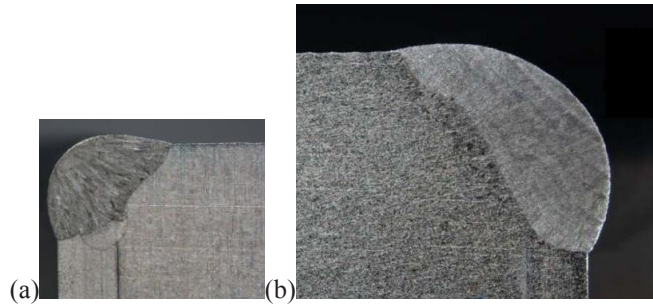


Fig. 10. (a) Joint 2 welded with laser orbital process; (b) Joint 2 welded with TIG orbital process

#### 4. Conclusions

A prototype laser welding head adapted to the specific requirements of the orbital welding process and tailored for tube-to-sheet joints used in the production of heat exchangers has been developed. The functionality of the ORBITAL system has been demonstrated: a circular movement of the laser beam over the joint is performed with high accuracy, a speed up to 5m/min, and real time control. The head is fixed onto the workpiece while welding, and so independent of any unpredictable movements or vibrations from the robot. The system also comprises a control software and a graphical user interface to select the welding parameters and check the status of the system during operation.

First welds were obtained for two joints made of Nickel alloys and austenitic stainless steel. The results were very positive. Good penetrated free of defect welds were achieved in both cases. The welding head permitted to achieve repetitive results in the positioning of the laser to the joint. The use of laser welding for the joining of tube to sheet joints was demonstrated to be possible. The tuning of each application must be performed carefully in order to ensure good weld geometry and precise positioning.

As a result of the ORBITAL laser welding head development, following improvements are expected for the heat exchangers manufacturing industry:

- Increasing productivity: reduction of welding cycle time by a factor of 10 regarding orbital TIG welding,
- Low heat input and reduced distortions,
- Fully automated process,
- Narrow deep penetration: high quality joints.

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